Anatomy of the Central Andes: Distinguishing between western, magmatic Andes and eastern, tectonic Andes

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Introduction: The Andes under the weight of a paradigm

Scientific activity and production take place under the light of paradigms (Kuhn, 1962) and the geosciences make no exception. Plate tectonics is the paradigm that currently governs our large-scale understanding of the Earth. Paradigms orient research at all scales, a phenomenon which geoscientists are rarely aware of. In the case of the Central Andes, most studies conducted since the late 1980s have admitted, explicitly or not, that crustal thickening has been primarily achieved through tectonic shortening of the South American margin, and thus that magmatic additions to the crust represented only a minor contribution to crustal thickening. Because this idea was particulary well developed in Isacks's (1988) landmark paper, this paradigm may be referred to as "the Isacksian paradigm". Since then, many researchers in the Central Andes have concentrated on tectonic shortening; however, crustal thickness cannot be accounted for by the available shortening estimates, especially in the arc and forearc (e.g., Schmitz, 1994; Sempere *et al.*, 2008, and references therein).

Yet, aside from the tectonic, i.e. mechanical, interaction of the converging plates, the other first-order characteristic feature of subduction zones is the production of arc magmatism. Simple logics implies that tectonic and magmatic processes should therefore be viewed as two related aspects of one same system. The idea that arc orogens are formed through magmatic accretion forced by subduction is widely admitted in island arc contexts (e.g., Tatsumi and Stern, 2006), but has only received minor attention in the case of the Central Andes — albeit with noteworthy exceptions (e.g., James, 1971b; Thorpe *et al.*, 1981; Kono *et al.*, 1989; James & Sacks, 1999; Haschke and Günther, 2003) —, a situation largely due to the dominance of the Isacksian paradigm.

The belief that the Central Andes originated by shortening has commonly biased cartography, for instance by forcing high-angle or poorly-exposed faults to be mapped as reverse faults and thrusts. Some areas were mapped in dramatically different ways by geologists who favored distinct models (e.g., Sempere, 2000; Wörner & Seyfried, 2001), and extensional structures were often overlooked. Moreover, observations and models from a variety of undoubtedly extensional settings in Europe and Africa now teach that some structural geometries previously thought to be typical of contractional processes, as in the Central Andes, in fact also occur in extensional contexts, in particular where normal faults were initiated as flexure-forming blind faults (e.g., Finch *et al.*, 2004). We have thus undertaken the revision of traditional mapping in southern and central Peru in order to better understand the detailed anatomy of this portion of the Central Andes.

"Western Andes" and "eastern Andes" in southern Peru

Southern Peru provides a convenient observatory for a detailed anatomy of the Central Andean Orocline (CAO). Identification and correction of mapping biases result in major revisions: the forearc, arc, and SW

Altiplano (henceforth "western Andes") appear to have been dominated by transcurrence (including transpressional deformation) and extension since ~30 Ma (Sempere & Jacay, 2006, 2007), in contrast with the NE Altiplano, Eastern Cordillera (EC), and sub-Andean belt (henceforth "eastern Andes"), where shortening has been indeed significant. Separating these two contrasting orogenic domains, seismic tomography detected a subvertical lithospheric-scale boundary in the northern Altiplano of Bolivia (Dorbath *et al.*, 1993) and in its prolongation, i.e. along the SW edge of the EC of southern Peru, the distribution of magmatic rocks (Sempere *et al.*, 2004) and the isotopic geochemistry of mantle-derived rocks (Carlier *et al.*, 2005) also mapped a subvertical lithospheric boundary, which coincides at the surface with the SFUACC major fault system (Fig. 1).

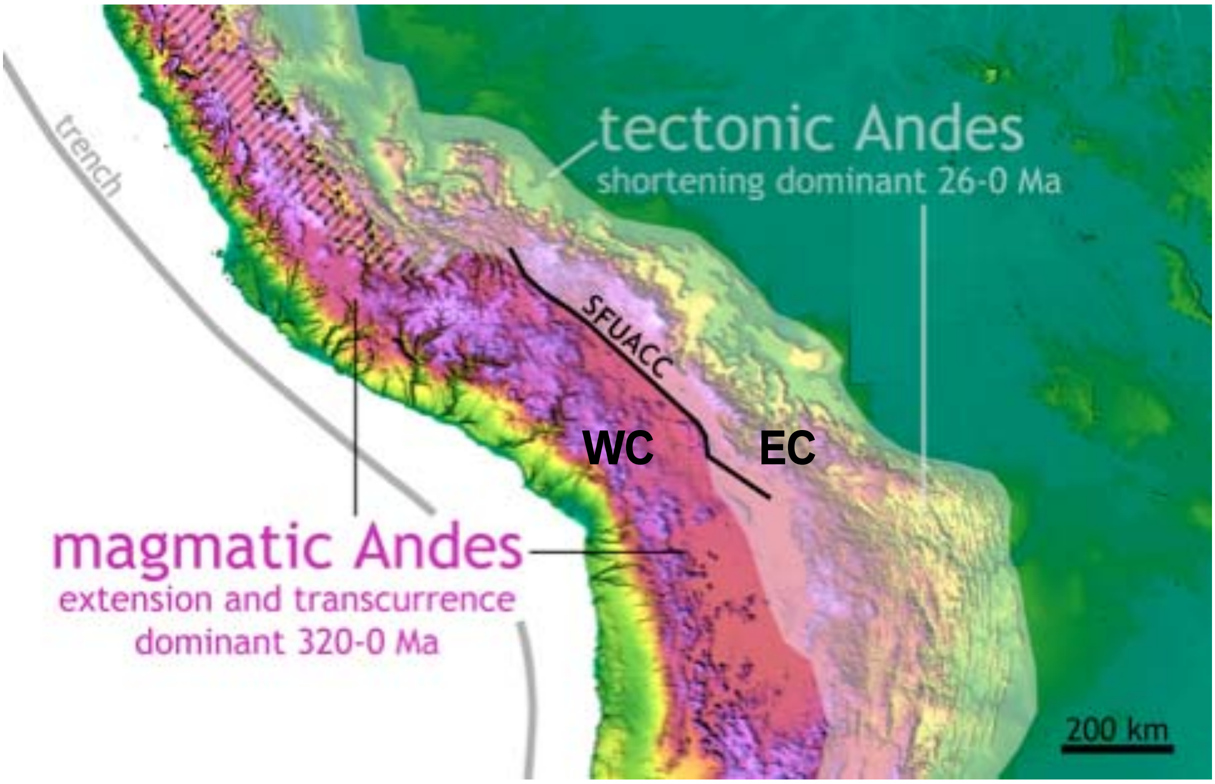

Figure 1. Approximate partition between the western, magmatic Andes and the eastern, tectonic Andes in the Central Andean Orocline. The magmatic Andes (forearc, Western Cordillera [WC], SW Altiplano) are characterized by little or no shortening and a crust thickest across the arc, whereas the tectonic Andes (NE Altiplano, Eastern Cordillera [EC], sub-Andean belt) display evident, substantial shortening. This implies that crustal thickening was achieved by magmatic accretion in the former, and by tectonic shortening in the latter. In southern Peru, the boundary between the magmatic and tectonic Andes is marked by the lithospheric-scale Urcos-Ayaviri-Copacabana-Coniri fault system (SFUACC in Spanish abbreviation), but may be transitional elsewhere. Hatched pattern: areas affected by Cenozoic shortening older than ~25 Ma.

In the western Andes, i.e. SW of the SFUACC, synorogenic basins formed in extension and along transcurrent faults. At least one low-angle extensional detachment, placing near-vertical Miocene conglomerates over a Cretaceous unit, occurs just west of Lake Titicaca (Sempere & Jacay, 2006). Significant transcurrent faulting, including transpressional deformation, developed along specific structures over southern Peru, including the western Andes. However, transpressional structures in the forearc and arc, such as the Cordillera de Domeyko in Northern Chile, can only account for relatively minor shortening and crustal thickening. The Pacific Andean escarpment is the locus of oceanward reverse faulting, suggesting incipient gravitational collapse of the WC (Wörner & Seyfried, 2001; Wörner *et al.*, 2002; Sempere & Jacay, 2006, 2007) instead of tectonic shortening.

A magmatic origin for the western Andes

Although the lack of surface evidence for significant shortening in the western Andes was accomodated in some graphic constructions by supposing blind crustal duplexes or insertion, at the base of the crust, of crustal slices tectonically displaced from the margin, no evidence has been obtained yet for any of such hypotheses, which appear to be largely paradigm-driven. The combined facts that in the western Andes the orogeny was accompanied by extensional and transcurrent tectonics, and that transpressional deformation cannot account for significant crustal thickening (as it produces only localized shortening), imply that the Isacksian paradigm, i.e. the assumption that the Central Andean orogenic build-up was mostly driven by tectonic shortening, has to be questioned in the western Andes.

A key insight into this issue is provided by the fact that in southern Peru the crust is thickest across the arc (Fig. 2), as demonstrated by seismic and gravity studies (James, 1971a; Kono *et al.*, 1989). Association of maximum crustal thickness with the arc region simply points to magmatism as the cause of crustal thickening in the western Andes, reinforcing previous similar interpretations (e.g., James, 1971b; Thorpe *et al.*, 1981; Kono *et al.*, 1989; Schmitz, 1994; James & Sacks, 1999), which unfortunately have been largely disregarded.

The idea that the arc crust was primarily thickened by magmatic mass transfer from the mantle is supported by the fact that the isotopic characteristics of most Andean magmas indicate that they largely consist of material extracted from the mantle (e.g., Pitcher *et al.*, 1985). Furthermore, I-type magmatism, a typical feature of Andean arc batholiths (Pitcher *et al.*, 1985), is now understood to result from the reworking of crustal materials by mantle-derived magmas, and is even viewed to drive the coupled growth and differentiation of continental crust (Kemp *et al.*, 2007). Crustal growth rates at arcs are now known to be at least 40-95 km^3/km.Myr (e.g., Tatsumi & Stern, 2006), i.e. at least twice the rates estimated by Reymer and Schubert (1984), who nevertheless mentioned a few cases with arc crustal growth rates as high as ~300 km^3/km.Myr. Volumes of volcanic rocks erupted at the surface were invoked to discard magmatic addition as a significant cause of crustal thickening, but updated estimates are much higher (de Silva and Gosnold, 2007); besides, no secure constraints are available on the ratio of volcanic volumes to total magmatic volumes, and this ratio might well be anomalously low in the case of thick crusts.

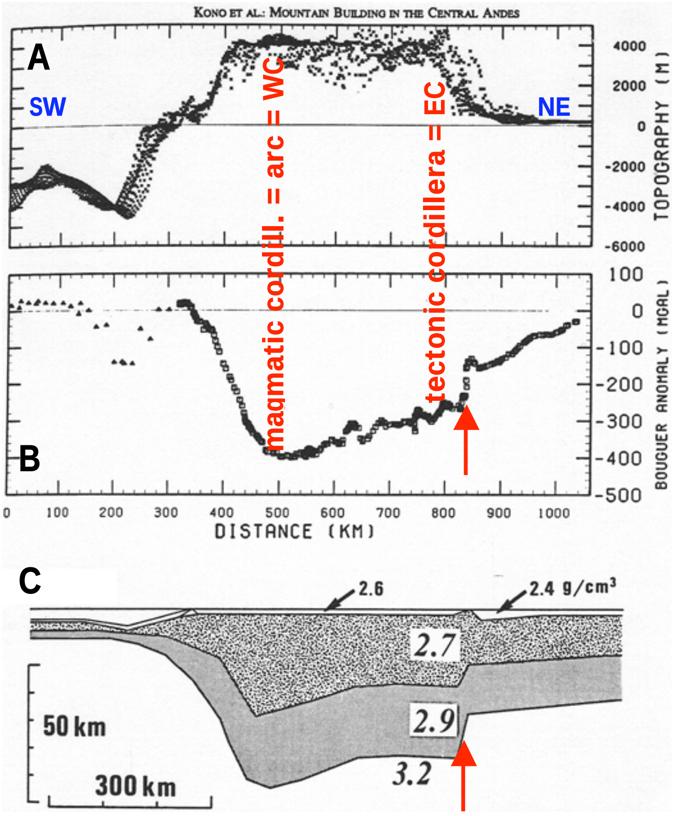

Figure 2. Topography (A), Bouguer anomaly (B), and distribution of crustal densities and thicknesses (C) in southern Peru, after Kono *et al.* (1989). Crustal thickness is clearly maximum across the magmatic cordillera (the volcanic arc, or Western Cordillera [WC]) and decreases toward the Eastern Cordillera (EC) across the Altiplano. The NE edge of the Eastern Cordillera, which is undisputably of tectonic origin, corresponds to a marked subvertical stair-step in the crustal structure (red arrows).

Conclusion

Updated geological mapping in southern Peru is confirming that tectonic shortening has been insignificant southwest of the SFUACC fault system, and certainly cannot explain the outstanding crustal thickening in the western Andes. The western Andes, which include the arc region, must therefore have formed by magmatic accretion, as already suggested by the abundant geochemical database. In contrast with the eastern Andes, which are indeed of tectonic origin, the western Andes have been built by magmatic processes, confirming previous but disregarded conclusions (e.g., James, 1971a,b; Kono *et al.*, 1989; Schmitz, 1994; James and Sacks, 1999). After all, crustal growth and orogenic build-up by subduction-related magmatism are known elsewhere to be common processes in island arcs as well as continental arcs (e.g., Tatsumi and Stern, 2006; Lee *et al.*, 2007).

References

Carlier, G., Lorand, J.P., Liégeois, J.P., Fornari, M., Soler, P., Carlotto, V., Cárdenas, J., 2005. Potassic-ultrapotassic mafic rocks delineate two lithospheric mantle blocks beneath the southern Peruvian Altiplano. *Geology* 33, 601-604.

de Silva, S.L., Gosnold, W.D., 2007. Episodic construction of batholiths: Insights from the spatiotemporal development of an ignimbrite flare-up. *Journal of Volcanology and Geothermal Research* 167, 320–335.

Dorbath, C., Granet, M., Poupinet, G., Martinez, C., 1993. A teleseismic study of the Altiplano and the Eastern Cordillera in northern Bolivia: New constraints on a lithospheric model. *Journal of Geophysical Research* 98: 9825–9844.

Finch, E., Hardy, S., Gawthorpe, R., 2004. Discrete-element modelling of extensional fault propagation folding above rigid basement fault blocks. *Basin Research* 16, 489–506.

Haschke, M., Günther, A., 2003. Balancing crustal thickening in arcs by tectonic vs. magmatic means. *Geology* 31, 933-936.

Isacks, B.L., 1988. Uplift of the central Andean plateau and bending of the Bolivian orocline. *Journal of Geophysical Research* 93, 3211–3231.

James, D. E. 1971a. Andean crust and upper mantle structure. *Journal of Geophysical Research* **76**: 3246-3271.

James, D. E. 1971b. Plate tectonic model for the evolution of the Central Andes. *Geological Society of America Bulletin* **82**: 3325-3346.

James, D. E. & Sacks, I. S. 1999. Cenozoic formation of the Central Andes: A geophysical perspective. In *Geology and Ore Deposits of the Central Andes* (ed. Skinner, B. J.), Society of Economic Geologists, Special Publication **7**: 1-25.

Kemp, A.I.S., Hawkesworth, C.J., Foster, G.L., Paterson, B.A., Woodhead, J.D., Hergt, J.M., Gray, C.M., Whitehouse, M.J., 2007. Magmatic and crustal differentiation history of granitic rocks from Hf-O isotopes in zircon. *Science* 315, 980–983.

Kono, M., Fukao, Y., & Yamamoto, A. 1989. Mountain building in the Central Andes. *Journal of Geophysical Research* **94**: 3891-3905.

Kuhn, T.S., 1962. *The Structure of Scientific Revolutions*. The University of Chicago Press, 172 p. (and later editions).

Lee, C.-T.A., Morton, D.M., Kistler, R.W., Baird, A.K., 2007. Petrology and tectonics of Phanerozoic continent formation: From island arcs to accretion and continental arc magmatism. Earth and Planetary Science Letters 263, 370–387.

Pitcher, W.S., Atherton, M.P., Cobbing, E.J., Beckinsale, R.D. (Eds), 1985. *Magmatism at a Plate Edge: The Peruvian Andes*. Glasgow: Blackie / New York: Halsted Press, 323 p.

Reymer, A., Schubert, G., 1984. Phanerozoic addition rates to the continental crust and crustal growth. Tectonics 3, 63–77.

Schmitz, M., 1994. A balanced model of the southern Central Andes. *Tectonics* 13, 484–492.

Sempere, T., 2000. Discussion of "Sediment accumulation on top of the Andean orogenic wedge: Oligocene to late Miocene basins of the eastern Cordillera, southern Bolivia" (Horton, 1998). *Geol. Society of America Bulletin* 112, 1752–1755.

Sempere, T., & Jacay, J. 2006. Estructura tectónica del sur del Perú (antearco, arco, y Altiplano suroccidental). Extended abstract, *XIII Congreso Peruano de Geología*, Lima, 324-327.

Sempere, T., & Jacay, J. 2007. Synorogenic extensional tectonics in the forearc, arc and southwest Altiplano of southern Peru, *Eos Trans. AGU* **88**(23), Joint Assembly Suppl., Abstract U51B-04.

Sempere, T., Jacay, J., Carlotto, V., Martínez, W., Bedoya, C., Fornari, M., Roperch, P., Acosta, H., Acosta, J., Cerpa, L., Flores, A., Ibarra, I., Latorre, O., Mamani, M., Meza, P., Odonne, F., Orós, Y., Pino, A., Rodríguez R., 2004. Sistemas transcurrentes de escala litosférica en el sur del Perú. In: J. Jacay, T. Sempere (Eds.), *Nuevas contribuciones del IRD y sus contrapartes al conocimiento geológico del sur del Perú*. Sociedad Geológica del Perú, Publicación Especial 5, 105-110.

Sempere, T., Folguera, A., & Gerbault, M. (eds.). 2008. New insights into the Andean evolution: An introduction to contributions from the 6th ISAG symposium (Barcelona, 2005). *Tectonophysics*, in the press.

Tatsumi, Y., Stern, R.J., 2006. Manufacturing continental crust in the subduction factory. *Oceanography* 19, 104–112.

Thorpe, R. S., Francis, P. W., & Harmon, R. S. 1981. Andean andesites and crustal growth. *Philosophical Transactions of the Royal Society of London* A **301**: 305–320.

Wörner, G., Seyfried, H., 2001. Reply to the comment by M. García and G. Hérail on "Geochronology (Ar–Ar, K–Ar and He-exposure ages) of Cenozoic magmatic rocks from northern Chile (18–22°S): Implications for magmatism and tectonic evolution of the central Andes" by Wörner *et al.* (2000). *Revista Geológica de Chile* 28, 131–137.

Wörner, G., Uhlig, D., Kohler, I., Seyfried, H., 2002. Evolution of the west Andean scarpment at 18°S (N. Chile) during the last 25 Ma: Uplift, erosion and collapse through time. *Tectonophysics* 345, 183–198.